

J/ψ production in association with a charm-quark pair at the Tevatron

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Abstract

I study the direct hadroproduction of J/ψ associated with a charm-quark pair at leading order in α_S and v in NRQCD. This process provides an interesting signature that could be studied at the Tevatron. I consider both colour-singlet and colour-octet transitions. I compare our results to the fragmentation approximation and discuss the associated experimental signatures.

1 Introduction

Inclusive J/ψ hadroproduction has been extensively studied in the theory of NRQCD [1, 2]. A well-known innovation of this theory is the colour-octet mechanism: the heavy-quark pair is allowed to be created in a colour-octet state over short distances, the colour being neutralized over long distances. It is thanks to this very mechanism that it is possible to account for the CDF data [3, 4] on the inclusive J/ψ and ψ' cross sections at the Tevatron [5, 6, 7]. However, the recent data collected at $\sqrt{s} = 1.96$ TeV by the CDF collaboration [8] have revealed that the J/ψ is unpolarised, in flagrant disagreement with the expectations of NRQCD. For a recent review on J/ψ production in hadron colliders, see [9].

Another challenge to theorists has been provided by the recent measurements at B factories (e^+e^- annihilation) [10]. Surprisingly, it has been measured by the Belle collaboration [11] that the associated production $J/\psi + c\bar{c}$ almost saturates the inclusive production:

$$\frac{\sigma(e^+e^- \rightarrow J/\psi + c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi + X)} = 0.59^{+0.15}_{-0.13} \pm 0.12. \quad (1)$$

It is therefore natural to wonder whether the corresponding production pattern could be large in hadroproduction as well [12]. Besides offering a new interesting signature, such as two leptons in association with one or two charm-quark tags, this process contributes to the α_S^4 (NLO) corrections [13] to the inclusive hadroproduction of J/ψ .

This note is organised as follows. In Section 2, we discuss the cross section and the polarisation of the J/ψ produced with a $c\bar{c}$ pair, via colour-singlet and colour-octet transitions, at the Tevatron. In section 3, we compare our result to the fragmentation approximation. In Section 4, we focus on the region of large transverse momentum and analyse the relevant experimental signatures in this regime. Finally, Section 5 is devoted to the conclusion of this note.

2 The calculation of $p\bar{p} \rightarrow J/\psi + c\bar{c}$

As for the case of open charm cross sections, heavy-quarkonium hadroproduction is dominated by gluon fusion at Tevatron energy. We have checked that the light-quark initiated process for $J/\psi + c\bar{c}$ production is suppressed by three orders of magnitude, and thus this contribution is neglected in the following.

In our numerical studies we have used:

- $\langle O_1(^3S_1) \rangle_{J/\psi} = 1.16 \text{ GeV}^3$;
- $\langle O_8(^3S_1) \rangle_{J/\psi} = 1.06 \times 10^{-2} \text{ GeV}^3$ and $\langle O_8(^1S_0) \rangle_{J/\psi} = 1 \times 10^{-2} \text{ GeV}^3$;
- $\mu_0 = \sqrt{(4m_c)^2 + P_T^2}$;
- $\text{Br}(J/\psi \rightarrow \mu^+ \mu^-) = 0.0588$;
- $m_c = 1.5 \text{ GeV}$;
- pdf set: CTEQ6M [14].

In Fig. 1 we show the P_T distributions of J/ψ at the Tevatron, both for the colour-singlet and colour-octet $J/\psi + c\bar{c}$ production. A cut on rapidity, $|y| < 0.6$, selects centrally produced J/ψ 's.

For the colour-singlet case, we note that the P_T distribution peaks at $P_T \simeq m_c$ and then it starts a quick decrease, dropping by four orders of magnitude at $P_T \simeq 20 \text{ GeV}$. We verified that the topologies where the J/ψ is produced by two different quark lines always dominate. This behaviour is similar to the J/ψ production at e^+e^- colliders, where the presence of two extra charmed mesons seems to indicate that the J/ψ is mostly often created from two different quark lines as well.

Contrary to the situation in e^+e^- collisions [15], the colour-octet production plays an important role for the associated J/ψ hadroproduction. Although negligible at small P_T , the $^3S_1^{[8]}$ transition starts to compete with the colour-singlet yield at $P_T \approx 10 \text{ GeV}$, and dominates the associated production at larger values of the transverse momentum of the J/ψ . The integrated colour-octet cross section remains small compared to the colour-singlet one, as a result of the suppression of the long-distance matrix element for colour-octet transitions.

The preponderance of the $^3S_1^{[8]}$ transition at large P_T is due to the kinematically-enhanced channel $gg \rightarrow c\bar{c}g \rightarrow c\bar{c}J/\psi$ where the J/ψ is produced via the fragmentation of a nearly on-shell gluon (see left-hand-side of fig. 2). In this fragmentation topology, the partonic subprocess behaves like $\frac{1}{P_T^4}$. The fragmentation of a gluon into a J/ψ is not allowed in the case of the α_s^4 colour-singlet production, which is therefore sub-dominant at large transverse momentum. The colour-singlet fragmentation of a charm-quark into a J/ψ (see right-hand-side of fig. 2) also behaves like $\frac{1}{P_T^4}$. However, in this case, the invariant mass of the products of the fragmentation is larger than in the case of the gluon fragmentation. The charm-quark fragmentation is therefore expected to be kinematically suppressed compared to the gluon one, as it is confirmed by the P_T spectrum in fig. 1.

The colour-octet 1S_0 transition has the same P_T shape as the colour-singlet production, but it is suppressed by one order of magnitude. Of course this suppression strongly depends on the values chosen for the long distance matrix elements. Nevertheless, in the following, we will consider that the intermediate state $^1S_0^{[8]}$ leads to a negligible cross section and will focus on the $^3S_1^{[1]}$ and $^3S_1^{[8]}$ transitions.

The polarisation of the quarkonium can be determined by analysing the angular distribution of the leptons. Defining θ as the angle between one lepton direction in the quarkonium rest frame and the quarkonium direction in the laboratory frame, the normalised angular distribution $I(\cos(\theta))$ is

$$I(\cos \theta) = \frac{3}{2(\alpha + 3)}(1 + \alpha \cos^2 \theta), \quad (2)$$

where the relation between α and the polarisation state of the quarkonium is

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}. \quad (3)$$

The parameter α for colour-singlet and colour-octet associated productions is displayed in fig. 1, right-hand-side. Whereas the J/ψ produced via a colour-singlet transition is unpolarized independently of the value of its transverse momentum, the transverse polarisation state dominates the colour-octet J/ψ production above $P_T = 5$ GeV. This feature is to be related with the polarisation studies for the α_s^3 inclusive colour-octet J/ψ production, which is also rapidly dominated by gluon fragmentation at large P_T .

3 Testing the fragmentation approximation

In the fragmentation approximation [16, 17], the cross section for the production of a J/ψ by gluon fusion via a parton i fragmentation is given, at all orders in α_S , by

$$d\sigma_{J/\psi}(P) = \int_0^1 dz d\sigma \left(gg \rightarrow i\left(\frac{P}{z}, \mu_{frag}\right) + X \right) D_{i \rightarrow J/\psi}(z, \mu_{frag}) \quad (4)$$

where $d\sigma\left(gg \rightarrow i(\frac{P}{z}, \mu_{frag}) + X\right)$ is the differential cross section to produce an *on-shell* parton i with momentum $\frac{P}{z}$ and $D_{i \rightarrow J/\psi}(z, \mu_{frag})$ is the fragmentation function of parton i into a J/ψ .

The fragmentation scale, μ_{frag} , is usually chosen to avoid large logarithms of P_T/μ_{frag} in $d\sigma$, that is $\mu_{frag} \simeq P_T$. The resummation of the corresponding large logarithms of μ_{frag}/m_Q appearing in the fragmentation function can be obtained via an evolution equation.

We now turn to the comparison of our results for the full LO cross sections for $p\bar{p} \rightarrow J/\psi + c\bar{c}$ with those calculated in the fragmentation approximation (without the evolution of the fragmentation function). The same set of parameters of Section 2 is employed¹. Let us comment the colour-octet $^3S_1^{[8]}$ production first (fig. 3, left-hand-side). In this case, the fragmentation approximation overestimates the differential cross section by 50% at $P_T \approx 5$ GeV. However the gap between the two curves decreases rapidly so that the fragmentation approximation starts to be accurate within 10% above $P_T \approx 12$ GeV. In the case of the colour-singlet production, the fragmentation approximation is lower than the full computation in the P_T range accessible at the Tevatron. We have verified that for J/ψ production, the two curves still differ by a little bit less than 10% at $P_T = 80$ GeV.

So, contrary to the colour-octet gluon fragmentation, the charm-quark fragmentation is not reliable in the kinematic region accessible at the Tevatron. Again, this feature, as well as the predominance of the colour-octet yield at large P_T , is intuitively clear, since the virtual mass of the intermediate parton is smaller in the case of the colour-octet gluon fragmentation, it indeed remains fixed at the value $2m_c$ (and so the fragmentation function is proportional to $\delta(1 - z)$).

4 Signatures at large transverse momentum

Given that a charm-quark hadronizes most of the time into a heavy-light quark bound state, the experimental signature of the process studied here is a J/ψ accompanied with one or two charmed mesons. At large transverse momentum, both colour-singlet and colour-octet transitions contribute. From the study of the polarisation in section 2, we know that the angular distribution of the produced leptons can be used to discern these modes of production. Another way to disentangle the two mechanisms is to study the distribution of events with respect to the angular separation between the J/ψ and the P_T -softest charm quark. We define $\Delta R^2 = \Delta\phi^2 + \Delta y^2$ to be the angular separation between the P_T -softest quark and the J/ψ . The resulting plots are displayed in Fig. 4.

¹For consistency, the coupling constant in the fragmentation function is evaluated at the scale $\sqrt{(4m_c)^2 + P_T^2}$.

For the colour-octet production, the P_T -softest charm-quark is most frequently emitted in the opposite direction of the J/ψ . This feature corroborates the validity of the fragmentation picture, where two gluons are emitted back-to-back, one of them giving rise to the J/ψ via a colour-octet transition, the other emitting an open charm-quark pair.

For the colour-singlet production, we see in fig. 4 that the angular distribution is quite different. There is a peak at $\Delta R \approx 0$, corresponding to the situation where a charm-quark is emitted in the same direction as the J/ψ . This contribution is (approximately) taken into account in the fragmentation approximation, and is particularly interesting. Indeed, it has been shown recently [18] that the cross section could be further enhanced in this region of the phase space, due to colour transfer between the unpaired charm-quark and one of the active quarks.

The rest of the distribution is pretty flat, indicating that, except at $\Delta R \approx 0$, there is no privileged direction for the charm-quark. Contributions in this region have also been partially considered through the study of the c -quark initiated process $cg \rightarrow cJ/\psi$ (see Fig. 5). Indeed, in this process, the initial c -quark originates from the splitting of a gluon into a pair of charm quarks collinear to the beam. One of the quarks interacts with a gluon to produce the J/ψ , the other quark is lost in the beam pipe. This configuration is included into the α_s^4 process $gg \rightarrow c\bar{c}J/\psi$, in the phase space region where one of the open quarks is collinear to the beam. A rough idea of this specific contribution can be obtained by requiring that one of the charm quark must have a small transverse momentum. In Fig. 6, we plot the full colour-singlet production together with the curve resulting from the cuts

$$P_T(c) < 2 \text{ GeV}, \quad \text{or} \quad P_T(\bar{c}) < 2 \text{ GeV}. \quad (5)$$

The curve associated to the presence of one soft- P_T open quark becomes subdominant at large transverse momentum of the J/ψ . This is expected, since the presence of the two propagators in the c -quark initiated process (Fig. 5) disfavors this mechanism at large P_T compared to a fragmentation configuration.

5 Conclusion

In this note, we have presented the tree-level calculation for the associated production of J/ψ with a charm-quark pair. This process offers a new interesting signature, that could be tested experimentally by measuring the fraction of quarkonium produced with at least one heavy-light quark meson. Both colour-singlet and colour-octet transitions a priori contribute, but can be disentangled by looking at the angular distribution of the leptons originating from the J/ψ , or by studying the angular separation between the J/ψ and the charmed mesons.

We have found that the charm-quark fragmentation approximation employed to describe $J/\psi + c\bar{c}$ production should not be applied in the range of transverse momenta reached at the Tevatron and analysed by the CDF collaboration. This approximation actually underestimates the full colour-singlet production by more than a factor four in the region $P_T \simeq 15$ GeV. On the other hand, the colour-octet gluon fragmentation is relevant in the region $P_T \geq 15$ GeV.

In conclusion, we look forward to the measurement of the fraction of events in the J/ψ sample at the Tevatron, with at least one charmed meson in the final state. Such a measurement could also provide further insight to the mechanism responsible for inclusive heavy-quarkonium production at hadron colliders.

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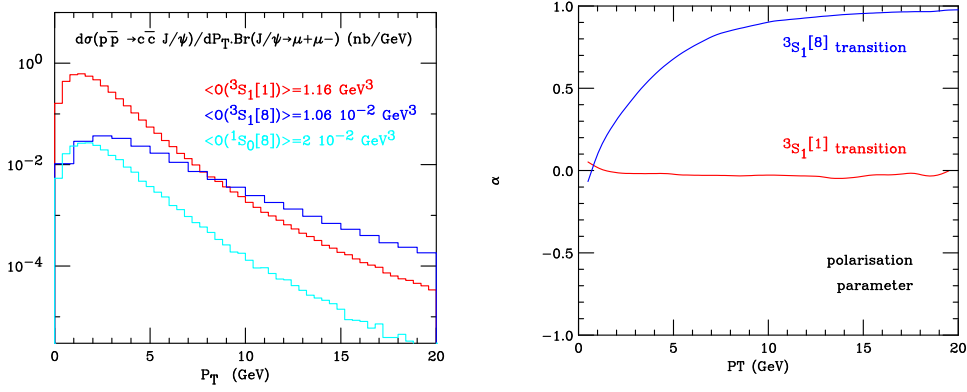


Figure 1: Left-hand-side: differential cross section for the process $p\bar{p} \rightarrow J/\psi + c\bar{c}$ at the Tevatron, $\sqrt{s} = 1.96$ TeV. Right-hand-side: polarisation parameter for the same process.

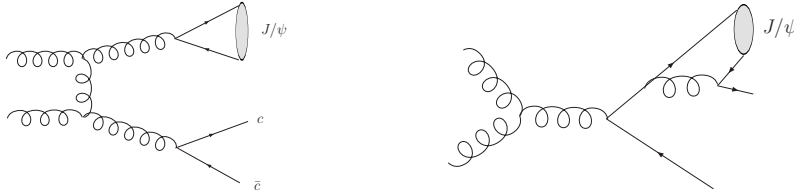


Figure 2: Left-hand-side: typical Feynman diagram for the colour-octet J/ψ production via the fragmentation of a gluon. Right-hand-side: typical Feynman diagram for the colour-singlet J/ψ production via the fragmentation of a (anti-) charm quark.

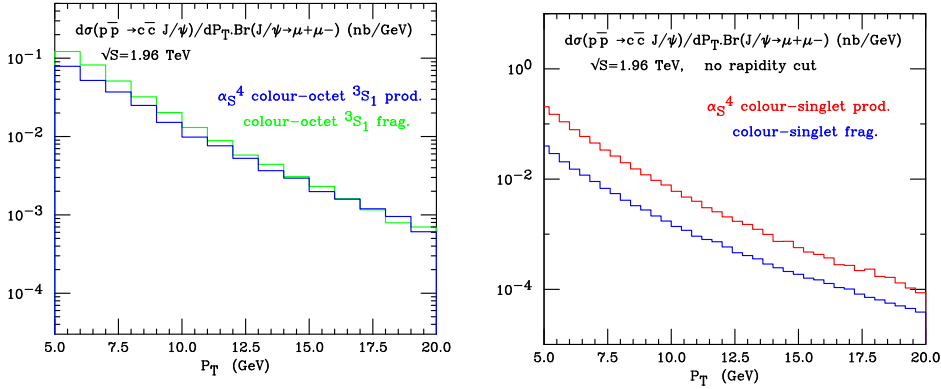


Figure 3: Comparison between the *full* LO cross section for $p\bar{p} \rightarrow J/\psi + c\bar{c}$ and the fragmentation approximation at $\sqrt{s} = 1.96$ TeV, for 3S_1 colour-octet transition (left-hand-side plot) and for colour-singlet transition (right-hand-side plot). No cut on rapidity is applied.

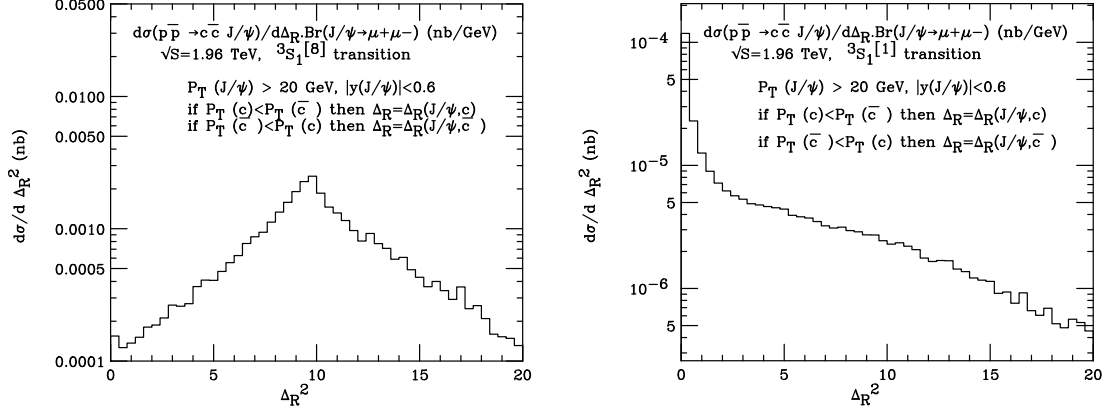


Figure 4: Angular separation between the J/ψ and the P_T -softest charm quark, for the $^3S_1^{[8]}$ transition (left-hand-side plot) and for the $^3S_1^{[1]}$ transition (right-hand-side plot).



Figure 5: Leading order Feynman diagrams for the c -quark initiated J/ψ production process.

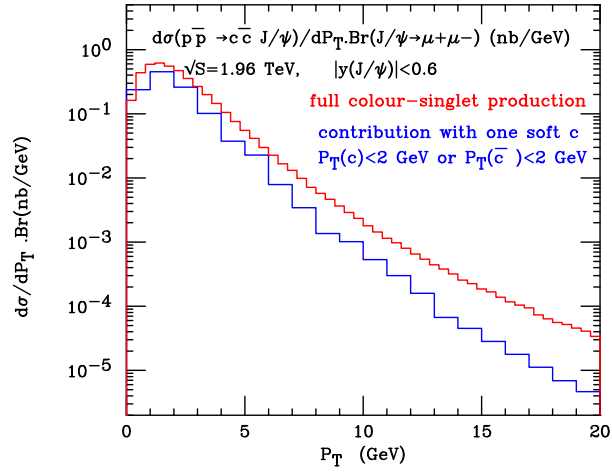


Figure 6: Red curve: full colour-singlet LO associated production. Blue curve: contribution from the phase space region where at least one open quark has a transverse momentum beneath 2 GeV.